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Possible effects of climate change on potato crops in Estonia

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The main objective of this research is to generate and analyse values of meteorologically possible yields (MPY, maximum yield achievable under given meteorological conditions) of potato for the middle and the end of the 21st century, at three Estonian locations. An early and a late potato varieties are analysed as examples. Climate change is evaluated under four different emission scenarios by 18 different GCMs; resultant changes are introduced into a dynamical potato growth model POMOD. The climate-driven changes without considering the effect of CO_2 concentration change are determined. A negative impact of climate warming on early potato growth in Estonia is confirmed. Moderate climate change scenarios will have a positive influence on growth of the late potato variety, whereas stronger changes will cause the decline of agrometeorological resources. A more positive or less negative effect of climate change is detected for northern Estonia.

Introduction

Changing of the climate system is now unequivocally acknowledged (IPCC 2007a). It is highly likely that this century will witness a rise in atmospheric CO_2 concentration, which will lead to a rise in the average global surface temperature, while changes in precipitation will be regionally different and less certain.

It has long been recognized that climate determines what kind of crops can be cultivated, whereas soils mainly indicate the extent to which the climatic potential can be realized. Therefore, one significant impact of climate change is its effect on agriculture. Trends in individual climate variables or their combination with agro-climatic indicators show that there is an advance in phenology in large areas of North America and Europe, which has been attributed to the recent regional warming (IPCC 2007b). The Intergovernmental Panel of Climate Change Fourth Assessment Report (IPCC AR4) also announces clear signals of reduced risk of frost, longer growing season, increased biomass, insect expansion, and increased forest-fire occurrence in temperate regions. According to most climate-change scenarios, the lengthening of the vegetation period and its earlier beginning can be expected for higher latitudes, including the Baltic Sea area.

Physically-based crop models have been widely used to explore impacts of climate change on potential food production and adaptation options at both global (e.g. Rosenzweig and Parry 1994, Hijmans 2003, Parry *et al*. 2004, 2005, Edmonds and Rosenberg 2005, Fischer *et al*. 2002, Parry 2007) and national or regional scales (e.g. Adams *et al*. 1990, Mela 1996, Harrison *et al*. 2000, Hoogenboom 2000, Olesen *et al*. 2000, Alexandrov *et al*. 2002, Reilly 2003, Cline 2007, Kaukoranta and Hakala 2008, Butterworth *et al*. 2010). The general conclusion is that climate change is likely to reduce global food potential.

Responses of different species to climate change can be different. Potato (*Solanum tuberosum*), one of the typical agricultural crops and main food crop in Estonia (Kotkas 2006), is best adapted to temperate climates. Therefore, temperature rise is generally expected to decrease overall yields (Haverkort 1990). However, Estonia, located in the temperate zone, is situated at its northern side and the most optimum areas for potato cultivation are currently lying south of these latitudes. A moderate rise of temperature can thus be expected to increase potato yields in Estonia, especially owing to the lengthening of the growing season (Kadaja and Tooming 1998). Due to its high water sensitivity, potato is also responsive to any changes in the precipitation regime, and a need for irrigation is supposed to become more frequent in many areas. In Estonia, the permanent excess water in soil accompanied by extreme precipitation can also cause significant yield losses (Saue and Kadaja 2009b).

In most climate change applications, long-term historical weather data, modified for different climate change scenarios, are used as input for the crop models. Usually, the outputs from the GCMs are used for these modifications (Robock *et al*. 1993). In this research paper, this approach is linked to the concept of the meteorologically possible yield (MPY) — the highest yield under existing meteorological conditions, expressing agrometeorological resources (complex of meteorological conditions, having influence on agricultural crop during a growing cycle, in chronological order), while the mean MPY value over a long period denotes agroclimatic resources, in yield units (Zhukovskij *et al*. 1989, Sepp and Tooming 1991, Kadaja and Tooming 2004). Previously, the concept was used to assess summer climate variability (Saue and Kadaja 2009a). The main objective of this paper is expanding those results into the future, generating and analysing future values of potato MPY, i.e. estimating changes in agrometeorological resources for potato cultivation. Since the impact of CO_2 increase on plants is not considered in the MPY calculations, the results reflect purely the climate-driven yield changes.

Material and methods

Climate change scenarios

For model simulations of future crop production, future weather data are required. To obtain temperature and precipitation data for the middle and end of the current century (hereafter marked briefly as projection for the target years 2050 and 2100), climate change scenarios for Estonia were generated using a simple coupled gas-cycle/aerosol/climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) that drives a spatial climate-change SCENario GENerator (SCENGEN) (http://www.cgd.ucar.edu/cas/wigley/magicc). MAGICC/SCENGEN is a software package that enables to investigate future climate change based on emission scenarios for greenhouse gases, reactive gases, and sulfur dioxide. MAGICC consists of the software that estimates the global annual mean surface air temperature and sea level rise for particular emission scenarios and determines the sensitivity of these estimates to changes in the model parameters. Thus, it is a tool for comparing the global implications of scenarios, which may be generated for any period between 1990 and 2100. SCENGEN is a regionilisation algorithm using a scaling method developed by Santer (1990), which constructs a range of spatially detailed climate change scenarios. The algorithm exploits three sources of data — the output from MAGICC, results from the CMIP3/AR4 archive of GCM experiments, and a dataset of observed global and regional climate trends from 1980–1999 at 2.5° × 2.5° resolution — to produce spatially detailed information on future changes in the temperature, precipitation and mean sea-level pressure. MAGICC/SCENGEN has been one of the primary models used by the IPCC since 1990 to produce projections of the future global mean temperature and sea level rise. We used ver. 5.3 of the software, which is in consistence with the IPCC AR4. Information on the basic properties of MAGICC has been

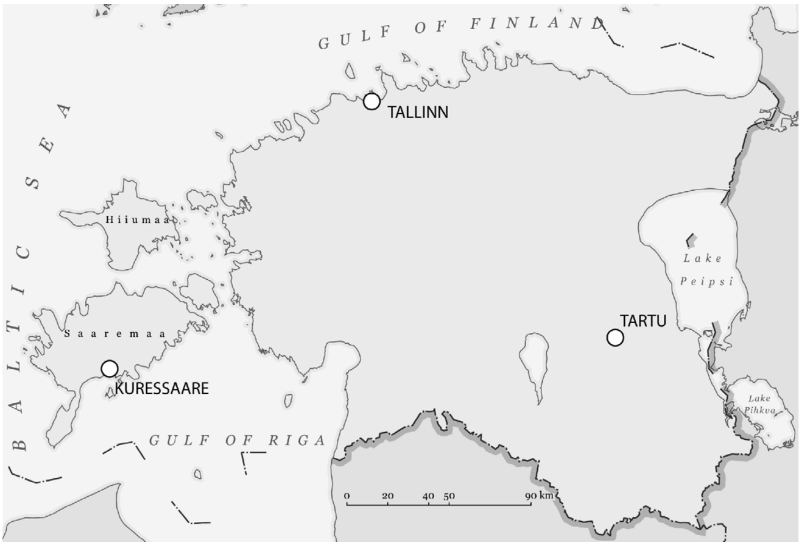

Fig. 1. Locations of the meteorological stations used in the present study.

published by Wigley and Raper (1992), Raper *et al*. (1996) and Hulme *et al*. (2000).

Because projections of climate change depend heavily on future human activity, climate models are run against scenarios. There are over 40 different emission scenarios in the Special Report on Emissions Scenarios (SRES) prepared by the IPCC (2001), each making different assumptions for the future greenhouse gas pollution, land-use, and other driving forces. Assumptions about the future technological development as well as the future population growth and economic development are thus made for each scenario (Nakićenović and Swart 2000). In running MAGICC/SCENGEN, the user can intervene in the design of the global or regional climate change scenario by: (1) selecting emissions scenarios; (2) defining the values for a limited set of climate model parameters in MAGICC that are important in determining the effects of uncertainties in the carbon cycle, the magnitude of aerosol forcing, the overall sensitivity of the climate system to external forcing, and the ocean mixing rate; (3) specifying the future time period for which results are displayed; (4) specifying the GCMs that are averaged to produce the climate change pattern information; (5) selecting an area or region for spatial averaging of climate change results. Four alternative illustrative emission scenarios were used in our study to generate climate change scenarios for Estonia: A1B, A2, B1 and B2. The highest climate warming is projected by A2, the lowest by B1. For each scenario, we exploited predicted changes in the mean monthly air temperature and precipitation from 18 IPCC AR4 GCM experiments (IPCC 2007a). Although currently there are 24 models in the CMIP3 database, only 20 have the full set of data required by SCENGEN. Of those 20, two more were excluded as suggested by the user manual (http://www.cgd.ucar.edu/cas/wigley/magicc) due to their poor performance as compared with that of the other models. In this study, the target years 2050 and 2100 (i.e., the central years for a climate averaging interval of 30 years) were chosen as the outcome years and the year 1990 was used as the reference year, and all the climatic changes are calculated with respect to this year.

The MAGICC/SCENGEN data are displayed at a grid resolution of 2.5° lat./long., thus the Estonian territory is covered by three grid boxes, with medium coordinates 58.8°N/21.3°E, 58.8°N/23.8°E and 58.8°N/26.3°E. We chose one meteorological station to describe each of those boxes: Kuressaare, Tallinn and Tartu, respectively (Fig. 1). Until 2001, manual observations had been carried out at those stations at 3-h intervals, (precipitation 12-h intervals). Since then, automatic stations have been in use at Tallinn and Tartu. As the Kuressaare meteorological station was closed in 2001, the data for the last years at this location were interpolated using measurements of the adjacent stations (Virtsu, Sõrve, Vilsandi, or Ristna, depending on highest correlation for a particular factor and period). Direct measurements of global radiation were carried out in Tartu, for other locations it was calculated using sunshine duration. Tallinn, Tartu and Kuressaare are located in regions with different local climates. Local climatic differences in Estonia result from, above all, the proximity of the Baltic Sea, which warms the coastal zone in winter and cools it especially in spring. According to the climatic classification of Estonia based on its air temperature regime, as proposed by Jaagus and Truu (2004), Tartu and Tallinn are located in the Mainland Estonia climatic region, characterized by a more continental climate, and Kuressaare is located in the Island Estonia region, with a much more maritime climate. Tallinn and Tartu fall into different climatic subregions. Tallinn is in a typically semicontinental subregion, where the continental influence prevails, but it is also influenced by the Baltic Sea. Tartu is located in the far hinterland in the continental subregion, with practically no climatic effect of the Baltic Sea. Spring is much warmer there, summer starts earlier and autumn months are colder. In addition to different temperature regimes, there are differences in precipitation and solar radiation between the stations, reasoned mostly by the influence of sea (Table 1). In seaside regions, typically characterized by Kuressaare, global radiation is higher and precipitation is typically lower than in inland regions, characterized by Tartu.

MAGICC/SCENGEN simulates monthly climate anomalies (mean future climate minus mean present climate). In our case, those anomalies are determined by 18 GCMs for each of the four scenarios and three grid boxes: absolute anomaly for temperature (°C) and relative for precipitation (%). To obtain future daily weather data, daily data of 45 years (1965–2009) were used as basic series. Further on, we use the term "reference period" to indicate that time interval. Adding corresponding monthly changes predicted by MAGICC/SCENGEN to each day's values, 18 series of 45-year-long datasets of air temperature and precipitation were obtained for each scenario and target year. From now on, we use the term "weather years" (as in Jame and Cutforth 1996) to refer to that new dataset. This way, not just the one average future set of predicted temperature and precipitation, but the possible weather distributions (4 scenarios × 18 GCM × 45 weather years = 3240 alternatives) are suggested for both target years. Global radiation was assumed not to change. Further, the crop model will calculate one set of outcomes for each weather year. Additionally, the sets of data obtained by using average climate anomalies over different GCMs were applied in comparative calculations.

Calculation of MPY

MPY of potato was computed for 2050 and 2100, using the production process model POMOD (Sepp and Tooming 1991, Kadaja and Tooming 2004). Photosynthesis and respiration blocks of this model as well as the system of yield categories containing MPY are based on the concept of maximum plant productivity (Tooming 1967, 1970, 1977, 1984, 1988). MPY is the maximum

Table 1. Mean values of average temperature and monthly sums of global radiation and precipitation at the three locations of the summer half-year in the period 1965–2009.

Month	Average temperature (°C)			Global radiation (MJ m^{-2})			Precipitation (mm)		
	Tallinn	Kuressaare	Tartu	Tallinn	Kuressaare	Tartu	Tallinn	Kuressaare	Tartu
April	3.8	3.9	4.9	394	399	380	35.6	32.7	33.4
May	9.7	10.0	11.0	587	591	555	41.3	29.7	54.9
June	14.3	14.6	15.1	626	626	595	59.7	43.9	71.8
July	16.7	17.1	17.1	601	608	580	83.0	57.9	70.7
August	15.7	16.7	15.9	467	484	452	78.9	61.6	79.8
September	11.1	12.4	10.9	270	284	265	76.1	65.7	60.0

yield conceivable under the existing irradiance and meteorological conditions with optimal soil fertility and agrotechnology with effects of plant diseases, pests and weeds excluded. Only the soil properties related to the determination of the soil water content are considered. POMOD computes the growth of plants and their organs using a time step of 1 day, whereas the photosynthesis calculation is performed using 1-hour time step. The feedback is expressed by the leaf area index (LAI) of the crop.

The input information for the model can be divided into four groups: daily meteorological data, annual information, parameters of location, and biological parameters of the potato variety.

As daily meteorological information POMOD needs data on daily mean air temperature, precipitation and global radiation. The weather years described above were applied to POMOD as input meteodata.

The same set of the computed weather data was employed to derive the annual information: the date when the soil moisture would fall below the field capacity and the temperature limits of the growth period: the dates of the permanent increase in temperature above 8 °C in spring and drop below 7 °C in autumn, and the dates of the last and first night frosts (≤ –2 °C). To calculate the future dates of night frosts, we composed relationships between mean daily air temperature and ground-level minimum temperature dependent on the radiation sum of the previous day, separately for spring and autumn periods.

The soil water status in the spring is determined by the date when soil moisture falls below the field capacity. To calculate this date, a relationship between simplified energy balance, R_{fc}, for the interval from permanent transition of temperature over 0 °C and soil moisture falling below the field capacity, and meteorological data was constructed. In R_{fc}, incoming global radiation and evaporative energy of precipitation (precipitation multiplied to latent evaporative heat) were accounted for. Using 30-year data of 13 stations from the Estonian Agrometeorological Network measuring soil moisture, the strongest correlations of R_{fc} were achieved with temperature sums from March to April ($T_{3–4}$) and precipitation sums from February to April ($U_{2–4}$) jointly in a multiple regression:

$$R_{fc} = 468.2 - 1.587T_{3-4} - 0.517U_{2-4}, r = 0.66 \quad (1)$$

There was no increase in r when the sums of global radiation were also included in this multiple regression.

Now, to determine the date of soil moisture drop below the field capacity of particular weather year, a submodel is calculating R_{fc} with Eq. 1 as well as the permanent date of temperature rise over 0 °C. Next, from that date, the running energy balance is summarized day-by-day. The date, on which it exceeds R_{fc}, is taken as the date when the soil field capacity has been achieved. This date is the initial day for soil water-balance calculations in the model. Also, the latest of these dates — the arrival of soil field capacity or a permanent increase in temperature above 8 °C — is considered the first possible planting date. As the aim of this article was to assess agrometeorological resources, we used the optimal planting date granting the maximum tuber yield in the meteorological conditions of particular weather year. That date is achieved by postponing the day of planting day-by-day from the first possible planting date until the maximum yield is obtained. To avoid stoppage at the secondary maximum, postponing will continue until MPY drops below 70% of its maximum value, or until the date of summer equinox. Following from the differences in variety parameters, the seeking process of the optimal planting date gives different results for early and late varieties. The crop cycle is terminated when the mean daily temperature falls below 7 °C, night frosts start (≤ –2 °C) on the ground surface, or tuber accretion is ended.

The location is characterized in POMOD by its geographical latitude and the hydrological parameters of the soil, such as the wilting point, field capacity, and maximum water capacity. We used the parameters of the field soils prevalent at the locality (Kitse 1978). For Tartu, the parameters of a region with Albeluvisol (World Reference Base for Soil Resources 2006) were used; for Tallinn and Kuressaare, the Skeletic Regosol prevails. All the soils are sandy silt loam, with quite similar hydrological parameters.

The model requires the parameters for the photosynthesis, respiration, and growth functions as the biological parameters of variety.

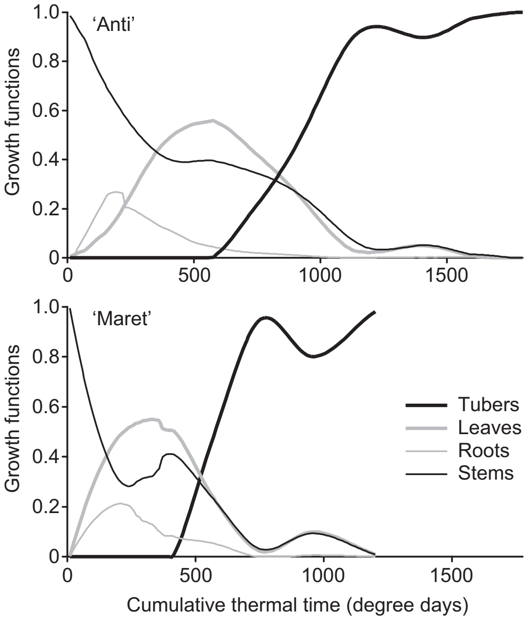

Fig. 2. Experimentally determined growth functions (distribution of growth increment of total biomass among plant organs) of the late potato variety 'Anti' and early variety 'Maret'.

We used the parameters of the early variety 'Maret' and the late variety 'Anti', both bred for Estonian conditions. The variety-specific photosynthesis variables — the initial slope of the photosynthesis irradiance curve a, the irradiation density of adaptation R_a, and the photosynthesis and respiration rates at the saturated PAR density given per unit mass of leaves, σ_1 and σ_2 respectively — were estimated initially relying on the literature data and then specified for the model by a calibration method on the basis of the experimental field data (Saue 2006). For 'Maret', we used the values $a = 0.069$ μmolCO_2 μmolPAR^{-1}, $R_a = 85$ μmolPAR m^{-2} s^{-1}, $\sigma_1 = 570$ μmolCO_2 kg^{-1} s^{-1}, $\sigma_2 = 57$ μmolCO_2 kg^{-1} s^{-1} and for 'Anti' $a = 0.101$ μmolCO_2 μmolPAR^{-1}, $R_a = 128$ μmolPAR m^{-2} s^{-1}, $\sigma_1 = 380$ μmolCO_2 kg^{-1} s^{-1} and $\sigma_2 = 38$ μmolCO_2 kg^{-1} s^{-1}. Growth functions (Ross 1966), describing the distribution of growth increment of total biomass among leaves, stems, roots and tubers (Fig. 2) and redistribution of biomass in the late stage of growth, were determined separately for the two varieties on the basis of field experiments carried out from 2001 to 2006 (Kadaja 2004, 2006a). The growth functions are applied to the model in a tabulated form, wherein the calendar time is replaced by the biological time expressed as the cumulative thermal time in degree days. Of course, uncertainties would arise from using empirical growth functions for generalisation (as from all the empirical parameters profusely applied in all crop models), however they sufficiently describe the varieties for which they were determined.

POMOD, written initially in FORTRAN and transferred later into the Visual Basic of Excel, has an open code and its output is not restricted. Considering the great number of calculations in this work, only the final MPY, maximum LAI and phenological dates were included in the output. One set of outcomes was calculated for each weather year. Statistical significance of MPY changes was determined with Tukey's HSD *post hoc* test which was carrid out for each scenario, location and variety over all the 18 GCM outputs and 45 years.

Table 2. Changes in annual mean air temperature and precipitation calculated as a mean of experiments by 18 different GCM for four different emission scenarios, averaged over three grid boxes. In brackets the range of projections (min–max) is given.

Year	Scenario	Temperature change (°C)	Precipitation change (%)
2050	A1B	2.38 (0.89–4.10)	8.3 (–3.4–34.3)
	A2	2.56 (0.98–4.39)	9.5 (–3.0–37.1)
	B1	1.72 (0.61–2.99)	6.0 (–1.9–24.7)
	B2	2.24 (1.05–3.61)	8.0 (–1.3–28.8)
2100	A1B	4.63 (2.12–7.54)	16.3 (–3.6–58.7)
	A2	5.74 (2.17–9.86)	20.2 (–7.9–82.4)
	B1	3.11 (1.62–4.83)	10.8 (–0.9–36.8)
	B2	4.09 (1.81–6.76)	14.5 (–3.6–54.6)

Results and discussion

Climate change

Results of the four illustrative greenhouse gas emission scenarios, each containing 18 GCM experiments used in SCENGEN, provide a range of possible climate change scenarios for the three considered locations in Estonia (Table 2). Averaged over the GCMs, all scenarios project the increase in the annual mean temperature, the

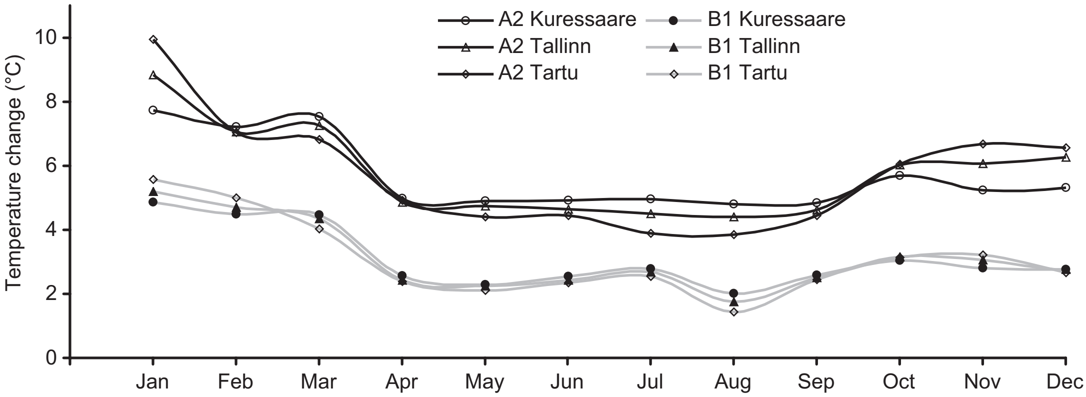

Fig. 3. Changes in monthly mean air temperature (°C) in Tartu, Tallinn and Kuressaare by the projection for 2100 calculated as a mean of experiments by 18 different GCM for emission scenarios A2 and B1.

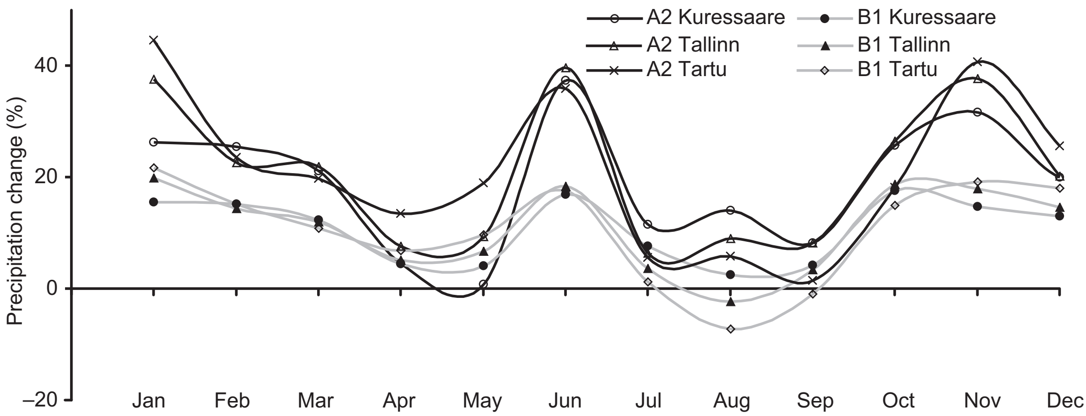

Fig. 4. Changes in monthly mean precipitation in Tartu, Tallinn and Kuressaare by the projection for 2100 calculated as a mean of experiments by 18 different GCM for emission scenarios A2 and B1.

highest warming is foreseen to take place during the cold period of the year (Fig. 3), whereas the increase in air temperature will be lower during the period from April to September. Average annual precipitation is also predicted to increase (Fig. 4). However, changes in the annual range of monthly precipitation vary highly between models and scenarios and are less certain than changes in temperature. On average, the highest change in precipitation is predicted for January and November. Of the summer half-year, June will be having the highest increase, while August and September are predicted to have a small increase or even a slight decrease. All the projected climatic tendencies have already been noted during the final decades of the last century (Jaagus 1998, 2006), indicating evident climate warming in Estonia. In previous studies using climate change evaluations (Tooming 1998, Keevallik 1998, Kont *et al*. 2003), a higher temperature rise for Estonia has been applied; however, moderate warming seems more realistic.

Change in potato yields

For the late variety 'Anti', the long-term basic MPY values, calculated using the unchanged historical temperature and precipitation data and describing the climatic resources for plant growth during the reference period 1965–2009, are 60.4 t ha^{-1} in Tartu, 57.9 t ha^{-1} in Tallinn, and 51.4 t ha^{-1} in Kuressaare. For the early variety 'Maret', these values are 44.4, 47.2 and 39.6 t ha^{-1}, respectively. The lower yields in

Kuressaare are mostly due to frequent insufficiency of water. The differences between late and early varieties are the highest in Tartu and the lowest in Tallinn. No significant trends were observed in the MPY series during this period, since the global warming in Estonia has so far mostly been expressed in the warming of winters (Jaagus 1998, 2006).

For the early variety, yield losses are predicted for both target years at all studied localities under all climate change scenarios by almost all single GCM outputs (Table 3), indicating the debasement of agroclimatic conditions for early potato cultivation. The highest losses — up to 38% in Tartu and 34% in Kuressaare and Tallinn — are predicted under scenario A2 by the year 2100. At all three stations, changes as compared with the current situation proved significant for all scenarios for both outcome years (Table 3). For late variety, 9%–11% rise in yields is predicted for 2050 in Tallinn by all scenarios, however the difference between the present and future yields is statistically significant only for two weaker scenarios. At other stations, the change is marginal. Tallinn seems to be the most scoring location also for 2100, when the negative effect of change on yields only appears for two stronger scenarios and is significant only in case of A2, while B1 causes 7% rise in the yield (however, not statistically significant). In Tartu and Kuressaare, all scenarios predict yield losses in 2100, the most radical scenario A2 over 20% as compared with the present yield.

There is a strong negative linear correlation between changes in MPY and predicted rise in temperature (Fig. 5). Correlation is stronger for the early variety and inland locations — Tartu and Tallinn — but there are correlation coefficients over 0.8 for all locations and scenarios in some months or month combinations. The periods with strongest correlations between mean temperature rise and MPY change are commonly June–July for the early 'Maret' and June–August for the late 'Anti'. However, some drift toward later periods is noticeable for seaside locations — Tallinn and Kuressaare — especially for target 2050. Also other potato modelling studies (e.g. Kabat *et al.* 1995, Hijmans 2003, Štastná and Dufková 2008) found that in most cases potato yields are related to temperature change.

Table 3. Changes in mean MPY (%) for different climate change scenarios and locations by the projections for 2050 and 2100 across the 18 models as compared with the values for the baseline period. Singificance of differences was tested using Tukey's HSD test; *p* values at which differences are considered significant are set in boldface.

Year	Scenario	Tallinn		Kuressaare		Tartu	
		Change (%)	*p*	Change (%)	*p*	Change (%)	*p*
Late variety 'Anti'							
2050	A1B	9.1	0.097	–1.3	1.00	0.1	1.00
	A2	8.5	0.17	–2.0	1.00	–0.5	1.00
	B1	10.9	**0.019**	1.8	1.00	2.5	1.00
	B2	10.5	**0.029**	0.6	1.00	1.0	1.00
2100	A1B	–3.3	0.98	–13.0	0.10	–13.9	**0.0011**
	A2	–13.0	**0.0015**	–22.1	< **0.0001**	–23.4	< **0.0001**
	B1	7.0	0.41	–3.5	1.00	–3.4	0.98
	B2	0.2	1.00	–10.4	0.36	–10.0	0.067
Early variety 'Maret'							
2050	A1B	–13.0	< **0.0001**	–15.6	< **0.0001**	–16.4	< **0.0001**
	A2	–14.4	< **0.0001**	–16.8	< **0.0001**	–18.1	< **0.0001**
	B1	–8.5	**0.0092**	–11.1	**0.020**	–11.3	**0.0010**
	B2	–11.9	< **0.0001**	–14.0	**0.0006**	–15.4	< **0.0001**
2100	A1B	–27.7	< **0.0001**	–27.2	< **0.0001**	–32.3	< **0.0001**
	A2	–34.4	< **0.0001**	–33.9	< **0.0001**	–38.8	< **0.0001**
	B1	–17.9	< **0.0001**	–19.0	< **0.0001**	**–22.?**	< **0.0001**
	B2	–24.3	< **0.0001**	–24.9	< **0.0001**	–28.7	< **0.0001**

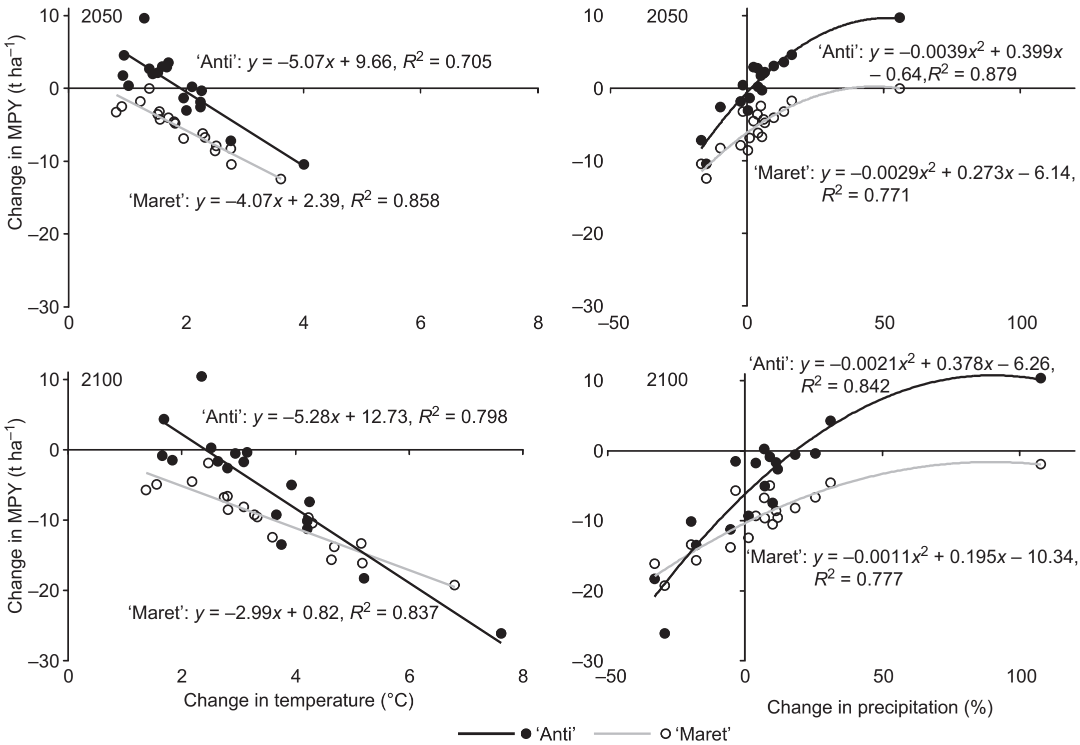

Fig. 5. Dependences of changes in MPY on changes in temperature and precipitation, proposed by the outputs of different GCM, in Kuressaaare by scenario B2 for the two target years. Changes in climate are chosen for the periods giving the highest correlation: in case of temperature from June to July for the early variety 'Maret' and from June to September for the late variety 'Anti', in case of precipitation from July to August.

Predominantly, positive correlation exists between MPY and rise in precipitation (Fig. 5). However, the highest changes in precipitation have already a negative effect and these correlations are better described by second order curves. Although the correlations proved significant for all locations, they are the highest for Kuressaare ($r > 0.7$), where yields are often affected by lack of water. The correlation is stronger there for the late variety 'Anti' and the target year 2050. However, the compensatory effect of precipitation among negative influence of temperature rise is quite small. Even at Kuressaare it is for different scenarios 0.5–0.9 t ha^{-1} for the early variety 'Maret' and 1.0–1.9 t ha^{-1} for the late variety 'Anti'. At the inland stations the importance of precipitation is even smaller. Of course, this is a generalization, since mean MPY is observed. When the results of different weather years and GCM outputs are considered, the picture becomes quite variable.

As was stated by Woodward (1988), the main effect of temperature is through the control of the growing period duration. Higher temperatures may shorten the duration of the growing season and the length of the growing cycle, decrease the CO_2 assimilation rate and increase the respiration losses. Predicted losses in MPY are indeed mostly attributable to higher temperature, which speeds the phenological development of the crop and reduces the time for leaf area development. As a result, future values of maximum LAI remain smaller than those calculated for the reference period (Table 4). Although a numerically smaller decrease occurs for the early variety, its originally smaller LAI value makes the impact of the decrease quite critical. Additionally, the acceleration of the development reduces the growing period of the early variety (Table 4), which is not limited in present conditions. Both the beginning and the end of the crop circle shift toward an earlier date, however the later shifts

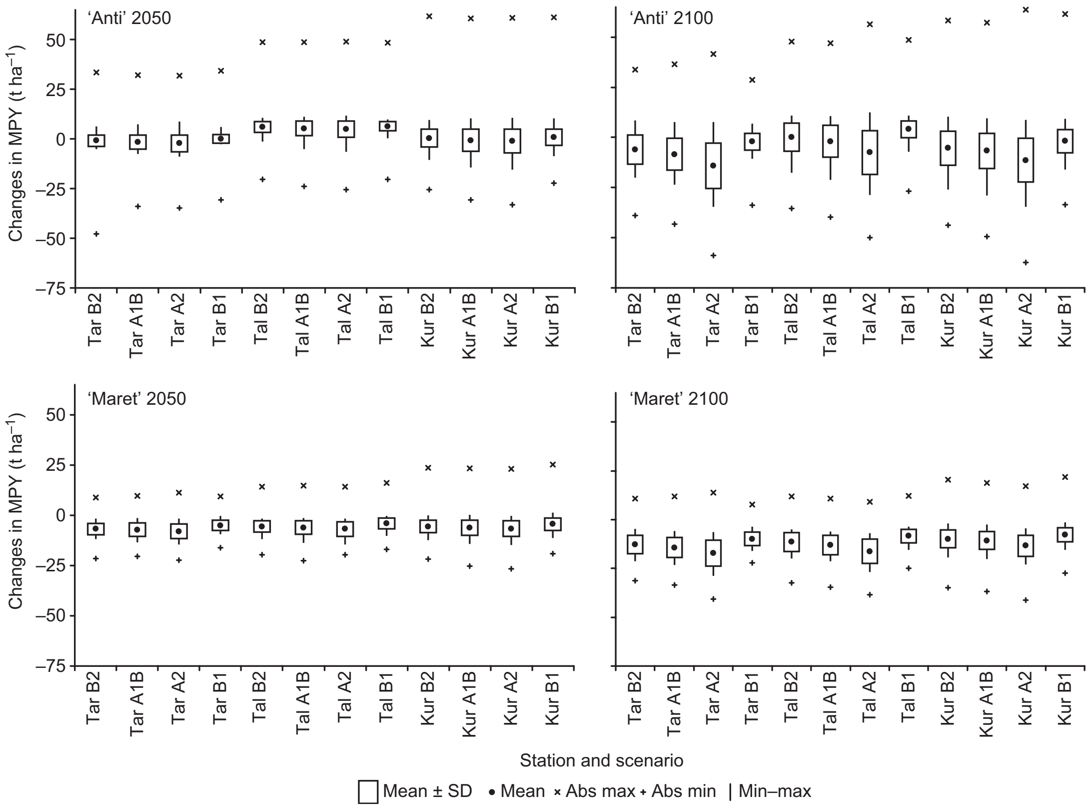

Fig. 6. Changes in mean MPY across 18 GCMs for the early potato variety 'Maret' and the late potato variety 'Anti' under four climate change scenarios (B2, A1B; A2, B1) for the three Estonian locations (Kur = Kuressaare, Tar = Tartu, Tal = Tallinn). Abs max and Abs min mark the absolute range of change in all models and weather years.

more. For example, for target 2100, the optimal sowing time shifts ahead by 5–16 days while the crop circle ends 26–36 days earlier, depending on the location. Although weather conditions allow to begin even a month earlier and harvest a month and a half earlier, it would lead to the decrease in yield. Contrary to that, the growing season of the late variety, which is today limited by the general temperature level and night frosts, extends in the conditions of global warming. This lengthening results from shifts both in spring and autumn; however, for the target year 2050 the increase is most pronounced in autumn, while for 2010 the increase is nearly equal in spring and in autumn. The duration of the growing season is expected to increase the most for

Table 4. Climate-change induced changes in maximum LAI and growing period; means for different scenarios are given.

Variety	Target year	Decrease in maximum LAI (%)			Changes in duration of growing period (days)		
		Tallinn	Kuressaare	Tartu	Tallinn	Kuressaare	Tartu
Late variety 'Anti'	2050	9.0	11.3	11.2	22	16	17
	2100	17.0	18.2	21.7	30	19	22
Early variety 'Maret'	2050	6.6	8.6	9.0	–8	–12	–11
	2100	14.9	14.9	19.3	–18	–20	–20

Tallinn, up to 22 and 30 days in 2050 and 2100, respectively.

There are quite large differences between contributions of single GCMs (Fig. 6). The highest MPY values are predicted by calculations predominantly based on the GISS-EH model, which prognoses large increase in precipitation and low rise in temperature for the summer period. In general, high MPY values for the late variety are produced by the models with moderate increase in summer temperature and precipitation, while early variety is favoured by low temperature increase and/or significant increase in precipitation in July. On the other hand, the HadCM3 model leads to the lowest MPY values for Tallinn and Kuressaare, due to the highest increase in temperature and considerable decrease in precipitation in July and August. For Tartu, the highest summer temperatures were predicted by the two models bringing about the lowest MPY values. The values of mean yields changes in Fig. 6 also suggest that for 2050 differences in yields are mostly related to location, while for 2100 the influence of the "outermost" scenarios has started to overcome the influence of location.

In previous similar works (Kadaja and Tooming 1998, Kadaja 2006b), a general rise in MPY of the mid-late variety 'Sulev' for low and medium climate change scenarios has been predicted; it was foreseen to be highest in northern Estonia (including Tallinn region) and was mainly attributed to the longer duration of the growing period. Greater increase in MPY was also predicted for the islands of Hiiumaa and Saaremaa (represented by the Kuressaare station in the current work), attributed to increased precipitation. The superiority of moderate warming for northern Estonia also emerges from our results. However, the increase of the yields in islands seems unlikely, since the general rise in precipitation turned out to be smaller and its distribution not so favourable for potato as it was predicted by the earlier versions of climate models (Keevallik 1998).

There were numerous studies on the possible climate change related changes in crop production in Europe, including potato production. IPCC (2007b) projected with high confidence that in southern Europe climate change would reduce crop productivity, while in northern Europe the initial effect of climate change was projected to increase crop yields. In a study on the possible climate-change induced changes in the global potential potato production (Hijmans 2003), decrease in potato tuber yield was predicted. However, at high latitudes, global warming is supposed to lead to changes in the time of planting, the use of later-maturing cultivars, and a shift of the location of potato production. The same tendencies were revealed by our research. In many regions, Hijmans (2003) predicted the future changes in potato yields to be relatively small, and sometimes positive. Similarly to our results concerning the late variety, Peiris *et al.* (1996) calculated increase in tuber yield due to the longer growth period resulting from temperature rise at a few sites in Scotland. Unlike our results reflecting only climate-driven yield changes, some authors point out that the increasing CO_2 concentration may reduce the negative impact of temperature rise and increase potato yield mainly at higher latitudes. Wolf (1999a, 2002) reported small to considerable increases in mean tuber yield in northern Europe being caused by the higher CO_2 concentration and temperature rise, but for central and southern Europe the positive effect of CO_2 enrichment may be counteracted by the negative effect of concomitant temperature rise. The latter is also valid under hotter and wetter scenarios for Great Britain (Wolf 1999b). Wolf and van Oijen (2002) showed yield increase for the year 2050 in all regions of the EU, mainly due to the positive yield response to increased CO_2. Reduction of positive effect of elevated CO_2 by elevated temperature was described by Rosenzweig *et al*. (1996) for most sites in the USA and by Miglietta *et al* (2000) for Dutch weather conditions. Also, some findings suggest that under field conditions positive effects of high CO_2 concentrations observed in the lab will prove to be considerably lower than previously expected (e.g. Long *et al.* 2006). The real magnitude of the CO_2 effect on C3 crops (including potato) is quite uncertain.

In the review by Olesen and Bindi (2002) it is concluded that although climate change scenario studies performed using crop models show no consistent changes in mean potato yield, an almost constant increase in yield variability is predicted for the whole Europe. A similar result for the present climate was achieved in our previous calculations with POMOD — we detected an increase in MPY variability in simulated potato series for the 20th century, indicating that the combined effects of weather conditions on plant production processes have more complex character than can be measured with long-term statistics for individual meteorological elements (Saue and Kadaja 2009a).

Also, in our calculations it is assumed that the historical weather data will represent variability in weather conditions in the future. Although variability of the climate in the future may change (Rind *et al*. 1989, Mearns 2000), inducing possible decrease in mean crop yields (Semenov and Porter 1995, Semenov *et al*. 1996), some researchers (Barrow *et al*. 2000, Wolf 2002) reported that, for potato, changes in climatic variability in northern Europe generally resulted in no changes in mean yields and their coefficients of variation (CV). In our case, variations in MPY series are generated by varying conditions of weather years and differences induced by using outputs of different GCMs. Future variability reasoned by weather years was similar to the variability in the reference series, 0.15–0.31. However, in the future series weather-induced CV decreased slightly for the late variety and increased for the early variety. Variation induced by differences among GCM outputs was smaller than weather-induced variability in case of the target year 2050 (CVs in the range 0.08–0.14) but was similar or even greater in case of target 2010 (CVs in the range 0.10–0.32).

Productivity of the early potato varieties is lower than that of the late varieties and our results suggest that this disadvantage is expected to increase with climate warming. Early-maturing potatoes are cultivated in Estonia mostly for their quick utilization; today their share is only 10% of the whole potato cultivation area. The reason for such disproportion is purely economical — due to the free movement of goods within the EU, cheap early potato is imported to Estonia from the south (mainly Poland) and it is thus not profitable for local farmers to grow. However, since the climate change perspective is also, and above all, expected to worsen agrometeorological resources for potato growth in the southern regions, the economic situation may in the future actually favour early potato growth in Estonia despite yield deprivation. Otherwise, the share of early potato is expected to continually decrease.

Conclusions

All four reviewed climate change scenarios project an increase in the annual mean temperature for Estonia, with the highest warming occurring during the cold period of the year. Average annual precipitation was also predicted to increase, although those changes appear less certain than the changes in temperature.

The impact of climate warming is negative for early potato growth in Estonia. All scenarios predict significant losses in potato yields at all three studied locations. The scenarios of higher temperature rise cause higher losses, mainly due to the accelerating development, smaller LAI and shortened growing period.

Moderate climate warming has a positive effect on the growth of the late potato varieties through prolonging the growing period. However, more radical changes lead to the decline of agroclimatic resources. A more positive (or less negative, in case of more extreme scenarios) effect of climate change is detected for northern Estonia (Tallinn).

By the end of the century, the uncertainty of computed yields, originating from the diffusion of GCM results, attains the same magnitude as the interannual variability.

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